A Case Study for Assured Containment

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***Abstract*—While incremental steps are being taken to integrate unmanned aircraft systems (UAS) into the various national airspace systems, much work remains to establish appropriate regulatory infrastructure that allows UAS larger than 55 lb to operate for commerce or hire. The magnitude of that effort is compounded by the wide-ranging variety of UAS types and possible applications, as well as the diversity in quality and provenance of UAS components. The FAA has suggested developing design standards tailored to specific applications and operating environments as an approach to facilitate integration and safe operation of some UAS.**

This paper introduces a case study to investigate design standards for a midsize unmanned rotorcraft operating in a rural environment. A key aspect of this study is the concept of using a certifiable containment system, different from a conventional geofencing application, to ensure that the unmanned aircraft does not escape its intended operational area. The proposed assured containment system is expected to reduce the effort needed to regulate some UAS that could not currently meet rigorous aircraft design standards and fall outside of the parameters for operation outlined in the proposed small UAS rule. This paper discusses how assured containment may be a useful approach to limiting risk and reducing an otherwise prohibitive certification burden to enable UAS operations in confined areas. The case study examines the potential effect the assured containment approach might have on airworthiness certification requirements.

Keywords—unmanned aircraft system; airworthiness; assured containment; hazard partitioning; agricultural UAS; case study

I. INTRODUCTION

Regulatory authorities around the world are making progress on developing new regulations for unmanned aircraft systems (UAS)[1]. Currently within the United States (US), UAS are authorized to operate commercially in the National Airspace System (NAS) on a case-by-case basis. The Federal Aviation Administration (FAA) has authorized some limited commercial use of small UAS, generally less than 55 lb, under Section 333 exemptions to Federal Aviation Regulations (FARs) [1] and under restricted category approvals for UAS with prior military certification [2]. These steps are important, but much work remains to establish the regulatory infrastructure needed to support certification of all commercial UAS.

According to the FAA's UAS roadmap, UAS operating in the NAS for commercial use, beyond Section 333 exemptions and small UAS operating within visual line of sight (VLOS), will require compliance with design and performance standards for airworthiness [3]. While research efforts are underway to develop aviation-grade systems for UAS, few, if any, meet reliability standards for conventionally piloted aircraft (CPA) [4-7]. As part of an incremental approach to gaining type-design and airworthiness approval, the FAA has suggested "developing design standards tailored to a specific UAS application and proposed operating environment" [3]. This research aims to develop design standards for midsize unmanned rotorcraft operating in rural agricultural environments. The goal is to provide

[1] In this paper, UA means a device used or intended for flight in the air that has no onboard pilot, and a UAS includes the aircraft and its associated elements related to safe operations, including control stations, control links, support equipment, payloads, flight termination systems, and launch/recovery equipment, as per [3].

a provisional means to facilitate commercial operations in the NAS, albeit confined, for UAS that could not currently meet demanding design standards required for CPA and fall outside the operational parameters of the proposed small UAS rule.

Toward that goal, this paper examines some fundamental ideas underlying operating limitations as a means to minimize risk for some commercial UAS operations. In particular, concepts building on geospatial containment (i.e., limiting the areas in which an aircraft is allowed to operate) may provide an expedient approach for developing simplified safety standards for confined operations, at least for UAS that cannot meet typical aircraft design standards. Confined operations include those over sparsely populated or remote areas (e.g., farmland or wilderness areas), or those in well-defined airspace corridors designated for particular tasks (e.g., pipeline inspection). The Class U airspace concept recently proposed by Atkins [8] is one such example.

This paper puts forward the concept of assured containment that does not rely on Class U airspace. An assured containment system is a localization system, independent of the UA autopilot system, which acts to keep the UA within given bounds. As posited here, an assured containment system can be realized by a smaller set of functions than in a typical autopilot, which facilitates certification quality safety arguments. Use of an assured containment system may ease the overall effort required to regulate a number of special purpose UAS, thereby expediting their entry into the marketplace.

In the assured containment concept, flight is confined exclusively within a predefined volume of airspace such that hazards outside of that volume (e.g., related to harming persons or property on the ground and interfering with air traffic) have been partitioned from other hazards inside of the volume. This is similar to using Class U airspace. Assured containment differs from the autonomous geofence in the Class U concept in that the assured containment system can maintain safety in a GPS-degraded environment, is independent of the primary flight avionics, has a limited number of clearly defined interfaces to those avionics, and has a smaller set of functions than a conventional autopilot, in order to facilitate certification. For example, a containment system may include elements that implement flight termination (e.g., an additional fuel cutoff valve) which interface with onboard UA engine control systems, but do not rely upon them. Ideally, such a containment system is sufficiently simple to make compliance with current system safety standards conceivable (hence, *assured containment*). Such a system does not rely upon a certified autopilot and other aviation-grade components, because such systems are not readily available.

This paper describes the concept of assured containment for UAS and introduces a case study to examine the implications of that concept on airworthiness requirements for confined operations. Section II presents a framework to discuss aircraft hazards and hazard partitioning, and Section III uses that framework to explain the effect of confined operations on safety requirements. Next, Sections IV and V describe assured containment and how it differs from the notion of geofencing. Section VI describes a case study underway to examine design requirements for an agricultural UAS equipped with an assured containment system. The paper concludes with Section VII, where potential benefits and limitations of the assured containment concept and case study expectations are presented.

II. HAZARD PARTITIONING

Understanding hazards that pose harm to people or property and ways to mitigate those hazards are at the core of every aircraft safety certification effort. FARs are designed to protect the occupants of aircraft (e.g., airworthiness certification and flight rules), occupants of other aircraft (e.g., rules to prevent collisions), and persons and property on the ground. The lack of people on board the UA eliminates a significant portion of the hazard space; however, rote removal of all corresponding FARs related to this hazard space is perilous because regulations that primarily protect against one hazard may also protect against several secondary hazards simultaneously. Care must be taken to analyze the effect of coupling between hazards.

This section introduces a simple framework to help illustrate risk controls for UAS using hazard sets and corresponding mitigations. This framework considers hazards in three main sets: hazards to people on board the aircraft, hazards to people in other aircraft, and hazards to people and property on the ground.

Hazard partitioning provides a way to divide hazards into groups that can be analyzed and, hopefully, mitigated independently. By using some means to maintain partitions, the expectation is that the total effort required to mitigate the hazards in separate sets is less than the effort required to mitigate all the hazards without the partitions. One example of hazard partitioning is the operational restrictions placed on agricultural aircraft used for crop dusting. Specifically, hazards to people on the ground are reduced by an operational restriction prohibiting flight over populated areas. The pilot on board is responsible for enforcing the operational restriction. Hazard partitioning is commonly practiced in aviation, although it is rarely identified explicitly as hazard partitioning.

Intuitively, a hazard partition is a grouping over a set of hazards where every hazard is in a group, and each hazard belongs to only one group. More formally, a partition of the set of hazards H is a set of nonempty subsets H_i of H that are pairwise disjoint ($H_i \cap H_j = \varnothing$ for i ≠ j) and whose union is all of H ($\cup_i H_i$), and thus collectively exhaustive and mutually exclusive. The partition is a structure that is motivated by the idea that grouping objects that are alike will enable comprehensive reasoning about all of the objects in a group at once.

As an example of hazard partitioning, consider the set of hazards for a CPA, denoted in (1) as H_{CPA}. As described above, those hazards can be partitioned into three subsets: hazards to people on board ($H_{onboard}$), hazards to people or property on the ground (H_{ground}), and hazards to people in other aircraft ($H_{other\_aircraft}$). This yields the relation in (1):

$$H_{CPA} = H_{onboard} \cup H_{ground} \cup H_{other\_aircraft} \quad (1)$$

$H_{onboard}$ takes into consideration the number of souls on board along with the purpose and nature of the operation (e.g., transportation, recreation, or acrobatics). H_{ground} and $H_{other\_aircraft}$ take operational context into consideration. Operational context refers to the external environment in which an aircraft operation or flight takes place. The environment encompasses airspace class and air traffic considerations (captured by $H_{other\_aircraft}$), as well as geographical and population characteristics of the overflown areas (captured by H_{ground}).

The partitions in (1) may be used to examine mitigations. For CPA, there is an inherent coupling of mitigations for $H_{onboard}$ and H_{ground} in the sense that mitigations intended to protect people on board the aircraft also serve to protect people on the ground. Given that most safety requirements are levied for hazard mitigation, the main hazards considered for CPA are $H_{onboard}$ and $H_{other\_aircraft}$. For commercial aircraft, $H_{onboard}$ mandates a certain minimum level of development rigor to mitigate catastrophic events, such as hull loss. Specific requirements for reliability and design assurance, required to avoid catastrophic events, vary on a sliding scale depending on $H_{onboard}$, but there is a decided minimum for commercial operations.

Because there are no souls on board a UAS (considering only uninhabited UAS), the hazard equation for H_{UAS} becomes as shown in (2), since $H_{onboard}$ is comprised of the empty set (assuming the UAS is below the threshold of economic loss).

$$H_{UAS} = H_{ground} \cup H_{other\_aircraft} \quad (2)$$

This equation is consistent with the ICAO position on aviation regulation for UAS as "ensuring the safety of any other airspace user as well as the safety of persons and property on the ground" [9], and avoiding other aircraft [3]. Equation (2) shows that hazard mitigations and hence airworthiness requirements for UAS are driven by H_{ground} and $H_{other\_aircraft}$, unlike CPA. If airworthiness requirements for UAS are developed from the existing airworthiness requirements for CPA, then standards intended to protect souls on board (e.g., seat belts) could be imposed on UAS. On the other hand, some FARs primarily for protection of people on board have a side effect of protecting those on the ground. Care should be taken in determining which CPA regulations might or might not apply to UAS.

III. HAZARD PARTITIONING AND CONFINED OPERATIONS

Hazard partitioning can be used to support development of regulations necessary to mitigate risk to people on the ground. A key technique for developing mitigations for the hazard set H_{ground} is to further partition it with respect to geospatial location based on operational area. That is, for confined UAS operations, the corresponding set of hazards, $H_{confined}$, can be partitioned into the set of ground impact hazards associated with operation within a specified area, H_{inArea}, and the set of ground impact hazards associated with operation outside of that specified area, $H_{outArea}$. The hazard equation for this operation is (3). Mitigation strategies can then be employed for hazards inside the specified area, separate from those for outside the area, as long as the partition is maintained and coupling across partitions, if present, is managed properly. Choosing a partitioning scheme that decouples hazards across partitions enables the development of mitigation techniques whose impact can be directly identified upon the hazards for which they were designed, thereby easing the complexity of the assurance argument.

$$H_{confined} = H_{inArea} \cup H_{outArea} \cup H_{other\_aircraft} \quad (3)$$

A UA can crash in an uninhabited area without safety consequences: hull loss presents no hazard to people on the ground, though the UA still potentially presents a hazard to other air traffic. In certification terms, hull loss in this instance is not catastrophic; in fact, hull loss has no safety implications. Ensuring that there are no people on the ground within this environment is an operational safety requirement: the UAS crew must constantly monitor that no people have entered the area that constitutes the UAS' range.

To employ this hazard partitioning scheme for UAS with a greater operational range within an environment in proximity to people, alternative methods are needed to ensure the separation of the hazard sets H_{inArea} and $H_{outArea}$. An assured containment system is one possible method that could work for UAS intended for confined operations. If the desired operational area can be precisely defined, an assured containment system can mitigate the hazards in $H_{outArea}$. If ingress and egress of persons and mobile property into the containment area can be controlled, then the assured containment system also can mitigate the hazard set H_{inArea}. An implementation of this idea involves an active system, whose behavior can be relied upon to ensure the UA never leaves the specified area.

IV. ASSURANCE CHALLENGES TO GEOFENCING

Geofencing is often proposed to control the overflown area of UAS [8, 10]. For UA flying beyond visual line of sight (BVLOS), it becomes necessary to have a means to verify the position of the UA. Even for UA flown within VLOS, additional means for ensuring the vehicle's state and location are often helpful to the pilot. With an *electronic geofence*, the UAS pilot can preselect both altitude and lateral boundaries for the UA operation. The geofence algorithm detects when the UA has transgressed this preset boundary or if transgression is imminent, depending on the implementation. In those cases, the geofence will either alert the UAS pilot to the boundary violation (so the pilot may take action) or issue a command to the UA to automatically terminate flight, return to a preset waypoint, or possibly replan its flight. Geofences are primarily implemented via software, in conjunction with the UA's autopilot; thereby using the same sensors, actuators and processor as the vehicle's primary autopilot system [11].

The lack of independence in the processor in any autopilot-implemented geofence leads to a clear single point of failure: if the autopilot system fails, either through software or hardware means, the geofence obviously fails. Simply moving the geofence to a separate processor is not sufficient to eliminate this mode of failure. A common dependence on the global positioning system (GPS) and inertial measurement unit (IMU) for navigation, as well as the use of the same actuators to implement the resolution strategy (e.g., flight termination or return to waypoint), will lead to a coupling between the geofence performance and the autopilot system. Even if redundant sensors and independent servo connections are introduced for the geofence, the switching logic between sensor input and servo output channels, as well as all timing protocols (e.g., watchdog timers) must be analyzed for correctness (i.e., agreement, validity, termination) as well as independence (e.g., common clocks, etc.). From a certification perspective, design and reliability requirements for the geofence would be tied to the autopilot system. Additionally, non-interference and independence arguments would have to be made (possibly over all autopilot functions) to ensure that the safety critical geofence cannot be adversely affected.

There has been much work done on developing reliable and fault tolerant guidance, navigation and controls algorithms for autopilots [12-17]. This work can possibly serve as a first step in attempting to establish an assurance argument for certification purposes. However, there are many subsequent issues that must be dealt with in addition to having fault tolerant controls algorithms present in an autopilot in order to enable certification. The computational platform upon which the autopilot is implemented, as well as the underlying operating system [18] and communications architecture [19, 20] must support the assurance case, and be amenable to making the independence or non-interference arguments necessary to illustrate that the safety critical function cannot be adversely affected. Fault tolerance in sensors [21] and actuators [22] must also be encompassed in the assurance argument, if they are shared by both safety critical and nominal functions.

Given that many UAS and their autopilot systems are composed of commercial-off-the-shelf products (some even open source), reaching levels of reliability and design assurance sufficient for airworthiness certification may be difficult to achieve [23-25]. Furthermore, sensor and actuator redundancy necessary to meet reliability requirements for certification may add complexity and additional constraints to the vehicle design that challenge size, weight and power constraints.

A hypothesis of this research is that the use of an assured containment system, independent of the autopilot system and navigation signal, may provide an opportunity to reduce the overall effort needed to regulate a number of special purpose UAS. For an assured containment system that has limited functionality and does not share autopilot system resources, any assurance arguments should cover a much smaller software implementation, and thus be more cost effective. This will also enable complex control algorithms to be fielded in the autopilot, while safety functions can then be segregated and maintained by the assured containment system. Further details and implementation notions for containment concepts are reviewed, and an assured containment concept, independent of the vehicle autopilot system, is developed in the next section.

V. Assured Containment

An assured containment system is a *localization* system that has a *certification quality safety argument*, which acts to keep the UA within given bounds, and may have a variety of strategies with which to do so (e.g., return to containment area centroid, hover, terminate flight, etc.). The *assured* part of the assured containment concept comes from being able to build a safety argument, sufficient for certification purposes, that the UA will remain in a specified area in the presence of common vehicle, autopilot, sensor and actuator failures. The independence of the assured containment system from the UA primary avionics enables the ease of the assurance argument, and may act to facilitate certification.

A containment system is comprised of sensors to determine the vehicle state information, decision logic to detect an anticipated breach of containment, and the means to control the breach of containment (e.g., flight termination). Additionally, the interfaces of the containment system with the nominal UA systems must be analyzed with respect to safety related issues (e.g., coupling, interference etc.). Positioning errors across different suites of sensors, noise and disturbance tolerances, and environmental effects must be incorporated into the containment system.

A containment system also includes the means by which the containment volume is specified. All operational procedures, human-machine interfaces and software required to set and validate the containment area must be validated as well. This is necessary because any incorrect entry may create an ill-posed containment volume, thus creating an unenforceable boundary. Finally, the procedures by which the containment volume is validated with respect to the actual physical volume is crucial. Maps of ground based obstacles in the containment area can be utilized to facilitate obstacle avoidance, but identifying and avoiding obstacles are not functions of the containment system.

In order to facilitate the assurance argument for the containment system and enhance certification efforts, the assured containment system will be independent of the UA autopilot system as well as other avionics, and will have an independent means by which to ensure the geospatial containment of the UA in the event of onboard autopilot, sensor, servomotor and connection failures. This way, no single failure in the UA's autopilot system will result in an automatic failure of the containment system: a primary value of the assured containment concept comes from being able to limit the UA's physical location in the presence of such failures. Furthermore, an assured containment systems is both *modular and reusable*, in that there is no critical coupling with the UA's primary onboard avionics systems (all flight termination systems are redundant, independent mechanisms). Thus, a single certification argument for the assured containment system can be used to enable an entire class of vehicles and autopilot systems for these types of confined operations.

In summary, an assured containment system consists of the hardware, software and operational procedures as well as the evidentiary material (e.g., safety analysis, reliability data, proofs, etc.) that demonstrate the system performs its intended containment function. As part of airworthiness certification, the assured containment system must be analyzed as a whole, including a documented, fixed design whose failure modes can be clearly understood, then mitigated or controlled. Ideally, the effort required to develop and certify the assured containment system, with its focused functionality, would be far less than the effort required for a conventional UAS autopilot system. Consequently, the safety burden for the UAS could be placed on the assured containment system, instead of on the autopilot system.

VI. CASE STUDY OVERVIEW

To examine the effect of confined operations on airworthiness requirements, a case study is underway to propose design requirements for a midsize UAS (maximum gross take-off weight of approximately 1000 lb) operating in a rural environment. In particular, the UAS is intended to spot treat crops in fields up to 160 acres, in a precision agriculture context. NASA has partnered with Dragonfly Pictures, Inc. and the University of North Dakota to conduct this investigation with the Dragonfly Pictures DP-14 tandem rotorcraft [26] as the operational aircraft. This platform was selected purposely to examine airworthiness requirements for a UAS > 55 lb, operating in reduced visibility and BVLOS conditions, to move beyond proposed rulemaking for small UAS and VLOS operations. Other certifications, including production and pilot certification, will also be required, but are beyond the scope of the study.

Precision aerial application was chosen because of the low-risk nature of the operation and strong economic projections for that industry [27]. The concept of operations for precision spraying is predicated on having knowledge about field conditions and crop health, such as would be documented in a prescription map. The flight plan for the spray operations would be based on such a map, as well as geospatial information about the field and ground-based obstacles.

All flight operations are restricted to within a designated containment volume around the field, shown in blue in Fig. 1. The containment volume can be thought of in the simplest case as a virtual, 3-dimensional dome or box surrounding the field that constrains the area of operation. A 400 ft altitude limit reduces, but does not eliminate, the probability of intruding air traffic, since altitudes less than 500 ft above ground level are not generally considered safely navigable [28, 29]. Steps must be taken to detect and react to other nearby airspace users, such as crop dusters who may be working adjacent fields.

Procedures prior to and during operation ensure that no people are in the containment volume during flight (e.g., visual observation by UAS crew), and an assured containment system ensures

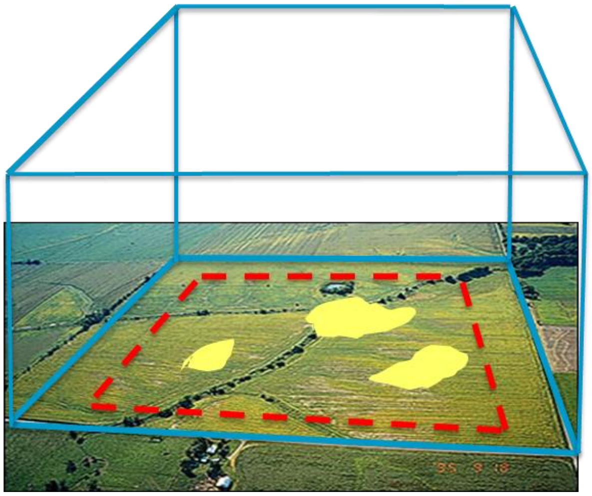

Fig. 1. Notional containment volume around operational area.

that the rotorcraft does not leave the designated boundary. Constraining the operation to a well-defined area, with provably limited possibility of impact with other aircraft or people, is key to limiting operational risk. Using a containment system to potentially reduce and simplify vehicle design requirements is the novel feature in this concept of operations.

An assured containment system, as described in Section V, does not exist in the UAS domain to our knowledge; though similar conceptual approaches are employed for unmanned commercial rocket launches. For the case study, an onboard system has been posited based on existing technologies, such that the system could be built. The current scope of the study, however, only extends to examining this system at the conceptual design level.

The proposed assured containment system operates independently of the UA autopilot system, and must be able to maintain safety in a GPS-degraded environment. The assured containment system activates flight termination only if it determines that the flight path will likely result in a breach of the containment boundary, whether due to an autopilot system anomaly, human error in flight path entry, or some other cause. The containment system posited here utilizes multilateration techniques that have many uses in UAS applications [30], including use in terrestrial GPS-denied environments [31]. The real-time UA position is determined by an onboard computer that operates independently of the primary navigation system (i.e., sensors, software, and power supply). This computer determines distance from three or more special low-power ground-based sensors that are positioned to give acceptable geometry and coverage for the operational area to be worked.

In this concept, the position computations are performed on board and compared to preloaded containment boundaries. If position and speed indicate that the boundary will be exceeded, a signal is generated to close a battery-powered electrical emergency fuel valve, forcing the UA to the ground. As a backup, an additional signal is sent from the ground control station to the onboard avionics system to close the primary fuel valve. Autorotation may be engaged; however, the autorotation function need not be a part of the flight termination aspect of the assured containment system. Because the UA is expected to operate at crop height most of the time, a forced autorotation should not result in much vehicle damage, though some limited crop damage may occur. If the UA is operating at or near the altitude limit at the time of containment system activation, damage to the vehicle could occur, along with release of high energy parts from the rotor system. The design of the containment area shape would take this possibility into account.

Work is currently underway to derive a set of proposed airworthiness requirements for the UAS, including requirements for the containment system. To the extent possible, processes and tools familiar to regulatory authorities and system safety experts are being used. The set of airworthiness requirements is being documented in the form of a mock type certification basis.

To date, requirements to be included in the basis have been reformulated from applicable parts of existing regulation, especially 14 CFR Part 27 [32]. Reformulation includes adopting some Part 27 paragraphs as is; proposing wording changes for some paragraphs; and, identifying other paragraphs as not applicable. For topics including controllability and maneuverability, structural integrity, and powerplant and fuel systems, relevant Part 27 paragraphs have been condensed. Lastly, new requirements have been drafted to address novel design features including the containment system, and also for systems for detecting and avoiding people and other aircraft, and for safety-critical datalinks.

Preliminary requirements for a containment system stipulate that such a system must mitigate the hazards associated with escape from the containment volume. Additional requirements address:

a) The accuracy of the aircraft's location relative to the containment boundaries,
b) Situational awareness of the UA's location relative to the containment boundaries,
c) Failure of infrastructure related to position information (e.g., GPS, cell phone network),
d) Means of detecting impending boundary violations,
e) Means of alerting the pilot in command,
f) Means of ensuring the UA remains within the established containment boundaries at all times; and,
g) Release of high energy parts that may constitute a hazard to bystanders outside the containment area.

The aim of the mock type certification basis is to serve as a starting point for discussion with regulatory authorities for developing a sound type certification basis for a UAS operating in confined environments. Further efforts are underway to develop a prototype assured containment system suitable for the DP-14 that could meet these requirements.

VII. CONCLUSIONS

Developing UAS-specific standards, including those for airworthiness, are essential to moving the process of integrating UAS into the NAS beyond the current practice of case-by-case accommodation. The concept of assured containment offers one possible approach to streamlined development of design standards tailored to UAS applications suitable for confined, uninhabited operational environments. The benefits of assured containment come largely from shifting the focus of airworthiness standards from protection of the physical air vehicle to a focus on the system that ensures the flight remains within a defined containment volume (that does not contain people).

In the agricultural case study, crashing a UA within the containment boundary is generally an economic concern, instead of a safety concern, because the assured containment system and procedures to keep people outside of the boundary ensure ground impact hazards are mitigated. Therein lies the potential for reducing the effort needed to establish design and performance criteria for UA built for such operations. That is, many of the airworthiness regulations for CPA intended to protect the physical aircraft are not necessary for UAS. This then allows the design of the UAS, aside from the containment system and supporting equipment, to be dictated largely by business considerations rather than safety considerations, allowing increased flexibility in design choices and cost tradeoffs. Because there are fewer safety requirements on the vehicle, there is a potential reduction in certification burden.

The assured containment concept could help enable a significant number of UAS to operate commercially in the short term that cannot qualify under anticipated small UAS rules and cannot carry the systems and equipment necessary for full integration in the NAS. Implicit in this approach is the need to specify a definite containment volume and to develop an assured containment system for the UA. Both seem imminently plausible. The agricultural UAS case study will shed some light on that plausibility, as well as the extent of the potential benefits from assured containment.

If the case study is successful, a streamlined approach to airworthiness certification for UAS could evolve that would allow midsize UAS to operate in confined regions near populated areas within the contiguous US. This would enable a host of commercial uses such as precision agriculture, herd management, natural resource exploration, as well as wind turbine, pipeline, and power line inspections. While this does not achieve full integration, such a step would allow the industry and regulators to start to gain valuable experience with UAS while carefully controlling access and potential harm to the aviation system as a whole.

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